

"Slow Light" and "Slow Current"

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It is shown that the effect of hole-burning under conditions of coherent population oscillations as well as the light pulse delay in a saturable absorber (a modification of the "slow light" effect) can be interpreted, in a comprehensive way, in terms of *intensity spectrum* of the light and *intensity-related susceptibility* of the non-linear medium. The physical content of these effects is illustrated by a simple electric circuit with a non-linear resistor which realizes a full analog of the saturable absorber. In this case the effect of hole-burning in the absorption spectrum of the medium is converted in to the effect of hole-burning in the frequency dependence of resistance of the non-linear resistor and the effect of "slow light" – in to the effect of "slow current".

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I. INTRODUCTION

At the end of the last century, there have been performed remarkable experiments [1, 2], that demonstrated the possibility to reduce the group velocity of light in a medium by many orders of magnitude. The idea of "slow light" has rapidly become extremely popular, gained a high prestige, and soon turned into a separate direction of quantum optics. In the first experiments on "slow light", the anomalously narrow dispersion feature of the atomic medium was created using the effect of electromagnetically induced transparency [3]. Later on, a different scheme of strong reduction of the group velocity of light has been proposed based on the so-called effect of coherent population oscillations (CPO) [4, 5]. The classical CPO effect is observed with the use of two monochromatic light beams, namely, the probe and the pump. The pump beam creates the spectral hole detected by the probe [6]. In the observations of the CPO-based "slow light", the pump beam is not explicitly used, but, nevertheless, the time delay of the light pulse is ascribed to the CPO-based hole-burning effect. In the papers [7, 8, 10], it has been shown that all manifestations of the CPO-based "slow light" perfectly match the simplest model of saturable absorber (see, e.g., [9]), which does not imply spectral hole-burning with appropriate modification of the group velocity of light. Still, the studies on the CPO-based "slow light" proceed, with the new interpretation of the pulse delay in a saturable absorber being regarded as self-evident. In our opinion, the possibility of such a revision of interpretation of a well-known effect of classical nonlinear optics is related to insufficiently clear understanding of physical nature of the hole-burning effect under conditions of the coherent population oscillations.

The goal of this paper is to demonstrate, in the most straightforward way, the fact that all manifestations of "slow light" in a saturable absorber, as well as the CPO effect are controlled exclusively by frequency dependence of its *intensity-related* response. It is important to emphasize that in terms of the intensity spectra, which allow one to describe this problem in a comprehensive way, neither the susceptibility of the system, nor the optical perturbation exhibit any spectral features at optical frequencies. Moreover, these effects cannot be considered, by any means, as specifically optical. As an example, we present a simple electric

circuit with a nonlinear resistor that realizes a full analogue of the saturable absorber in the field of the light wave including the effect of hole-burning in the absorption spectrum (converted into the effect of hole-burning in the frequency dependence of the resistor's resistance) and the effect of "slow light" (converted into the effect of "slow current"). The proposed analogy makes it possible, in our opinion, to better understand physical content of the effects under consideration.

In this paper, we will talk only about "slow" light, keeping in mind that all the results are equally valid for the so-called "fast" light (the light with a superluminal or even "negative" group velocity) upon sign inversion of the intensity-related nonlinearity of the system (i.e., upon replacing the bleachable absorber by the inverse one).

II. SATURABLE ABSORBER: BASIC PROPERTIES

By the saturable absorber is usually meant a layer of an optical medium whose transmission \varkappa varies with intensity I of the light, following, as a rule with some delay, its variations. As follows from the name of the saturable absorber, its absorption exhibits saturation with growing light intensity, though here this fact will be of no importance. In the most general form, the relation between intensities of the incident (I) and transmitted (I_{out}) light can be expressed by the formula

$$I_{out} = \varkappa(I, t)I \quad (1)$$

and the dynamics of establishment of the equilibrium transmission is given by the conventional relationship

$$\dot{\varkappa} = \frac{\varkappa_{eq} - \varkappa}{\tau} \quad (2)$$

where τ is the relaxation time of the absorber. To describe the effects under study, it suffices to restrict oneself to the case of small variations of the light intensity δI in the vicinity of I_0 and to consider a "linear" saturable absorber, with its stationary transmissivity \varkappa_{eq} linearly varying with δI :

$$\varkappa_{eq}(I) = \varkappa_0(I_0) - \varkappa_1 \delta I, \quad (3)$$

In the framework of these simple assumptions, one can easily find the amplitude and phase characteristics of the intensity-related response of the saturable absorber (Fig. 1). These curves represent frequency dependences of the amplitude $|K(\omega\tau)|$ and phase $\phi(\omega\tau)$ of the light intensity modulation at the exit of the saturable absorber under condition of harmonic modulation of the light intensity at the entrance.

As seen from the figure, the spectrum of such an "intensity susceptibility" displays a single feature lying in the range of low frequencies comparable with the inverse relaxation time τ (for more detail see [7]).

We want to attract special attention to the fact that this approach uses only the notion of the light intensity (the field amplitude squared), whose spectrum has no spectral peculiarities at optical frequencies. For this reason, this solution does not contain explicitly either optical characteristics of the light beam (spectral composition, degree of monochromaticity), or spectral properties of the absorber at optical frequencies (structure of the absorption spectrum, the nature of the band broadening, etc.). At the same time, this model describes comprehensively the CPO effect, as well as all manifestations of "slow light".

Indeed, the phase and amplitude characteristics of transmission for the intensity-modulated light passing through a saturable absorber studied in the papers on the hole-burning in a homogeneously broadened band and on "slow light" [4, 5, 11, 12, 13, 14], precisely agree with the above model and do not require to invoke the effect of hole-burning in the optical spectrum of the absorber.

The same can be said about the light pulse delay in the saturable absorber – the effect that is regarded as the main evidence for the group velocity reduction and for the "slow light" effect. Since in the range of low modulation frequencies ω , the phase delay $\delta\phi$ linearly varies with frequency, the time delay $\delta t = \delta\phi/\omega$ ceases to be frequency-dependent. As a result, the light pulse, whose intensity spectrum lies within the interval $\delta\omega \ll \tau^{-1}$, displays practically pure temporal shift with no reshaping.

In the conventional CPO effect, the weak modulation of the light passing through the saturable absorber is created using two monochromatic waves with close frequencies, one of them strong (pump wave) and the other weak (probe wave). This intensity-modulated light in this case, evidently, exhibits all the amplitude and phase changes mentioned above. But now, one detects variations in the optical spectrum (rather than in the intensity spectrum) of the transmitted light. This possibility is provided by the fine spectral structure of the light. Now, it becomes important that for the sufficiently low modulation frequencies (for the probe light frequency being close enough to that of the pump), the transmissivity of the medium is modulated at the difference frequency, and the light passing through such a modulator acquires additional spectral components, with the frequency of one of them being exactly coincident with that of the probe wave. As a result, the probe beam exhibits, in the vicinity of the pump wave frequency, an effective dip of the absorption spectrum (the appropriate spectral feature is also displayed by the phase behavior of the probe wave). It is this dip that is considered to be responsible for all manifestations of "slow light" in a saturable absorber.

In fact, we may conclude that physical content of the effects of CPO and "slow light" is confined to transformation of the intensity spectrum of the light transmitted through the saturable absorber in accordance with the transfer function shown in Fig. 1.

It should be noted that observation of the CPO effect, generally, does not necessarily imply real population oscillations, because the mechanism of the nonlinear dependence (1) may be not related to the light-induced changes in population of the initial state of the optical transition. Such a dependence may result from, say, a temperature shift of the optical spectrum that changes the overlap of the spectrum of the light beam with the absorption spectrum of the medium with increasing pump power, provided that the medium is heated due to nonradiative relaxation of the excitation. In other words, the saturable absorber, under conditions of the modulated pump, is capable of demonstrating coherent oscillations of losses, rather than populations. Moreover, this effect is, by no means, specifically optical and can be observed on nonlinear systems of other physical nature.

To get a clearer idea about the so-called effect of "hole-burning" in the optical spectrum of a saturable absorber and about attendant effects of "slow light", let us turn to a simple nonlinear system that has nothing to do with optics but realizes an isomorphic model of the saturable absorber.

III. "SLOW CURRENT"

Consider the electric circuit shown in Fig. 2. The key element of the circuit (which actually simulates the saturable absorber) is the resistor R , whose resistance varies with temperature which, in turn, follows (with some temporal delay) the power released on the resistor. By the input signal, we will mean the voltage U applied to the circuit and by the output, the voltage U_{out} falling on the resistor ρ (proportional to the current in the circuit):

$$U_{out} = \frac{\rho}{R + \rho} U \equiv \varkappa U \quad (4)$$

Here, the transfer coefficient \varkappa is the counterpart of transmissivity of the saturable absorber (see Eq. (1)). The dynamics of this coefficient is controlled by the equation

$$\dot{\varkappa} = \frac{\varkappa_{eq} - \varkappa}{\tau} \quad (5)$$

Here, τ is the relaxation time and \varkappa_{eq} is the equilibrium value of the transfer coefficient.

We will assume that for small variations of the input voltage δU in the vicinity of some value U_0 , the equilibrium value of the coefficient \varkappa_{eq} varies linearly with δU :

$$\varkappa_{eq}(U) = \varkappa_0(U_0) - \varkappa_1 \delta U, \quad (6)$$

One can easily see that the relation between the input and output voltage, in this case, is completely equivalent to that between intensities of the input and output light in the saturable absorber (see Eqs. (1–3)), and the quadripole described above realizes analog of the saturable absorber in the field of the light wave. Indeed, the amplitude and phase transformations of the input voltage modulation, in this circuit, are controlled by the same transfer functions (Fig. 1), whereas a sufficiently long pulse (in the scale of inverse relaxation times) of the input voltage modulation will exhibit a time delay, thus demonstrating the effect of "slow current" (if the resistance falls with increasing temperature, then the pulse of the current is delayed with respect to the voltage). Note that the fullness of the analogy is not hindered by the absence of the high-frequency carrier, which excludes any possible role of the "hole-burning" effect.

As one can easily see, however, no essential changes occur if the dc modulated voltage is replaced by a ac modulated voltage by filling the envelope with a high-frequency carrier. In this case, all specific features of the low-frequency response of the quadripole to the modulation of the effective voltage will remain the same (including the effect of "slow current"), but simultaneously there will appear the possibility to analyze transformation of the spectra of the high-frequency carrier by "slow" nonlinearity of the system. Using this circuit, one can easily make the experiment similar to that described in classical papers on observation of the hole-burning effect under conditions of the coherent population oscillations. For this purpose, one should apply to the input of the circuit two high-frequency signals with close frequencies (the "pump" voltage and the "probe" voltage), and detect at the exit only the weak "probe" voltage. In this kind of experiment, one will observe a narrow peak of current in the range of the "probe" frequencies close to that of the "pump". This peak can be interpreted as the effect of "hole-burning" in the frequency dependence of resistance of the nonlinear resistor R .

Figure 2 (a–d) schematically shows characteristic types of transformation of a modulated signal by the above electric circuit.

IV. CONCLUSIONS

In this paper, we have made an attempt to vividly demonstrate the fact that the effect of coherent population oscillations, as well as all manifestations of "slow light" result exceptionally from the "resonance" of the intensity-related susceptibility of the absorber at zero frequency. This spectral feature of the intensity susceptibility is really capable of modifying spectral composition of the light passing through the absorber (to the extent of modification of its intensity spectrum), which is revealed in the effect of "hole-burning" in the homogeneously broadened absorption spectrum. However, the question about possibility to treat this hole as a usual spectral feature of a linear absorption spectrum and, in particular, to apply to it the Kramers-Kronig relations needs special consideration. Specifically, as we already pointed out in [7], the possibility to detect the "hole" using standard absorption spectroscopy may depend on the internal phase structure of the light beam. In any case, we are not aware of experiments in which the effect of the pulse delay was observed in the presence of the pump beam. As for the "slow light" effect observed with a single light pulse, which, according to [4], combines the functions of the pump and probe beams, we see no grounds, in this case, to invoke the effect of coherent population oscillations for explanation of the pulse delay. We believe that the physical nature of the effects considered above is convincingly demonstrated by the proposed analogy between the saturable absorber and the nonlinear resistor in the electric circuit. This circuit simulates the effects of "slow" and "fast" light (depending on the sign of the temperature nonlinearity of the resistor), as well as the above effect of "hole-burning". This model simultaneously shows that the light pulse delay is not connected with effects of propagation and that it is inappropriate to invoke the notion of group velocity to interpret the effect.

FIG. 1: The amplitude and phase spectra of intensity susceptibility of the saturable absorber.

FIG. 2: Electrical analog of the saturable absorber and the main types of transformations of the modulated voltage without (a and b) and with (c and d) the carrier frequency. The dashed lines on the right plots show time dependences of the input voltage.

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